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A study of electrical aspects of neural conduction with an emphasis on the phenomenon of pain

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THESIS

A STUDY OF ELECTRICAL ASPECTS OF NEURAL CONDUCTION WITH AN EMPHASIS ON THE PHENOMENON OF PAIN

by

Stephens W. Nunnally, Jr.

December 1992

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A Study of Electrical Aspects of Neural
Conduction with an Emphasis on the
Phenomenon of Pain

by

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ABSTRACT

A study of the electrical nature of neural communication is performed. The study provides a background for the evaluation of an electrical mechanism, set forth by the author, as a possible explanation for the effect of acupuncture. The electrical and biological processes involved in the conduction of the nervous impulse, as well as the limits of understanding of those processes, are studied. The role of the arrangement of individual neurons into the human nervous system is examined. Also, the phenomena of pain and referred pain are investigated.

TABLE OF CONTENTS

I. INTRODUCTION

Pain and physical suffering are inherent in the operation of a military force. Previously, the military has managed the relief of pain primarily through the use of narcotic medications. The control and application of these medicines is technically and logistically difficult, and may impact the ability of a military unit to perform its mission. Drugs are prone to theft and abuse. Therefore, they must be stored and maintained in an environment of extreme security. These security measures restrict the portability and use of the medicines. Also, only a finite supply, which is further impacted by a finite shelf-life, is carried by a military unit. The use of narcotic medications results in a number of undesirable physiological effects. They often cause allergic reactions, or even death in a small percentage of the population. They have an adverse affect on vital physiological functions, and often cause loss of consciousness. They have long recovery times, cause a *drug hangover*, during which the ability of the individual to function is impaired, and can have possible long-term side effects. Any simpler, more effective, or more versatile method of relieving human pain would be of tremendous value to the military in increasing its operational ability. For all the high-technology hardware and software used by the military today, man is still the weapon system.

Acupuncture is an alternative method of pain relief which holds tremendous potential advantage for the military. The practice of acupuncture utilizes stimulation of subcutaneous tissue to block pain. The patient remains conscious, can cooperate with transport and surgery, and, in an emergency, can continue to function until the situation allows for further treatment. All other senses continue

to operate normally, and there is no equivalent to the drug hangover after treatment. The equipment used in acupuncture is small, portable, reusable, and could be used by minimally-trained non-medical personnel in an emergency.

The ability of acupuncture to provide relief from pain in varying degree for large numbers of patients has been proven by its successful implementation over a period of thousands of years. The fact that it does work is widely acknowledged by western medical professionals. The single, definitive reason why it is effective is still unknown, or at least not agreed upon, not even by those scientists or medical professionals who concede that acupuncture does work. If the underlying mechanism of acupuncture were known, it is very likely that the mechanism could be augmented to increase the effectiveness of acupuncture in relief of pain and to increase the number of patients on whom its use is effective.

In 1984, the author proposed the following theory as a possible explanation of the mechanism responsible for the phenomenon of acupuncture.

> Since acupuncture is performed using small metal needles, these needles might function as both antennas suitable for receiving background electromagnetic radiation (random noise) and as wiring to couple such noise into the conduction paths of pain signals in transit from the injured or ailing areas of the body's limbs or organs to the brain. The received noise signal might garble or obscure the pain signal sufficiently to prevent the brain from interpreting any information from that signal. The manipulation of needles used in acupuncture might function to keep the electrical connection clean as the body attempts to chemically repel the foreign body of the needle. The needles used in acupuncture are of different sizes, shapes, and materials, varying with the intended use. Thus, different antenna and wiring parameters can be obtained for modifying the reception and conduction of electrical noise to achieve more precise interference with the target pain signal. Background electrical noise varies in frequency components and strength by geographical area. This could explain why acupuncture seems to work only at some times and in some places with some patients [Ref. 1].

This thesis reports on research done to acquire background information for the evaluation of this theory. Areas of knowledge to be examined to provide a base of knowledge from which to evaluate the proposed theory are:

- a study of acupuncture and its practice
- the method by which acupuncture evolved
- previous theories as to the acupuncture mechanism
- the biological and electrical nature of neurons and the nervous system
- the manner in which the nervous system conducts signals
- electrical models of neural communication
- limitations on the understanding of these areas
- alternative and/or new theories of neural functioning
- the phenomenon of pain
- the current level of understanding of the electrical nature of the perception and transmission of pain

The material in this thesis does not report the results of original experimentation performed by the author. Instead, it presents an ordered set of ideas and best guesses retrieved from the intersection of the fronts of the expanding fields of biology and electrical science. These ideas are used to evaluate the feasibility of the proposed electrical acupuncture mechanism theory.

II. ACUPUNCTURE

A. OVERVIEW

Acupuncture is the practice of treating physical ailments by the stimulation of subcutaneous tissue at specific locations on the body. Usually, small metal needles are used for the stimulation. However, stimuli of pressure, heat, cold, ultrasound, high frequency electromagnetic radiation, and even laser beams have been used with varying degrees of success to provide the stimulation. The word *acupuncture* comes from the Latin *acus* (needle, particularly one used in surgery) and *punctura* (a pricking).

Acupuncture developed into a credible, viable medical treatment in the Orient as a result of its use on literally millions of patients over a period of thousands of years. Both the effectiveness of acupuncture and a metaphysical explanation for its underlying mechanism are widely accepted as fact in China. Although practiced outside the Chinese community in the United States since the 1930's, the existence and practice of acupuncture was relatively unknown in the U.S. before about twenty years ago. Since its introduction to this country, acupuncture has been used on an increasingly widespread basis by the medical community with a great deal of success. In fact, the effectiveness and viability of acupuncture is accepted widely in the United States and most other Western countries, albeit grudgingly. However, the accompanying oriental, metaphysical explanation of the mechanism by which it works is not accepted in the West. Much scientific research has been performed to find this underlying mechanism, most notably in Japan, France, Canada, Great Britain, and the United States. As of

yet, no single physical explanation has been offered that satisfies the majority of that subset of scientists and physicians who believe that acupuncture actually works.

B. HISTORY

The practice of acupuncture is thought to date back to the late stone age. It is believed that acupuncture began as a response to the observation that certain areas of the skin become sensitive when a corresponding organ or area of the body becomes unwell. The techniques of its practice, and the "understanding" of its underlying mechanism, were improved by trial and error as acupuncture was practiced over a period of centuries. Historical records from the excavations of different Chinese dynasties confirm the development and refinement of the practice as time progressed.

The definitive textbook and reference manual for teaching and practicing acupuncture is the *Nei Ching* (*Classic of Internal Medicine.*) By tradition, the work is credited to the legendary founder of China, the Yellow Emperor (Huang Ti, circa 500 BC). However, the multi-volume treatise probably was compiled over several centuries, and completed around 200 BC. Acupuncture had been so refined by the time *Classic of Internal Medicine* was written that the text is so accurate that it is still a primary reference for both Eastern and Western acupuncturists to this day. It is still published in America by Williams and Wilkins in Baltimore.

Chinese communists had acquired firm control of the government by 1952. Many traditional aspects of Chinese life were abandoned as the country struggled to modernize itself and feed, house, clothe, educate, and provide health care for its millions of citizens. Government hospitals and medical programs abandoned

ancient folk treatments and strove to adopt modern medical methods after the fashion of industrial and post-industrial nations. However, acupuncture continued to be practiced away from the major cities; in the small villages in the vast rural regions of the country. Mao Zedong (Mao Tse-tung), chairman of the communist party, became concerned that Chinese society had lost much of its uniqueness and Communistic focus by the struggle to modernize. Mao had been favorably impressed by the use of acupuncture during the "Long March" of 1934-1935 when the communists had fled 6,000 miles across China ahead of pursuing Nationalist forces. In 1958, Mao ordered that acupuncture be practiced in government hospitals and medical programs, and that much research be done on acupuncture. He planned to increase its effectiveness, range of application, and its value as a symbol of Chinese culture and national pride. This point marks the beginning of the practice of acupuncture as it is thought of in the West.

New texts were written and official schools and training programs were started. Thorough, disciplined searches were made to verify known acupuncture points, meridians, and stimulation methods and to discover new ones. The known limits of acupuncture were stretched tremendously by ambitious staffs of hospitals and medical programs to win political favor. Based on its long history of successfully relieving pain, its use was broadened to complement the use of chemical anesthesia. At first acupuncture was used to ease post-operative pain; later it was used as a supplement to chemical anesthesia. Eventually, acupuncture replaced chemical anesthesia altogether for some operations on some patients. By the end of 1958, a tonsillectomy had been performed using acupuncture anesthesia. By 1959, acupuncture anesthesia had been used for major surgical procedures. The more industrious the claim regarding an unprecedented,

successful implementation of acupuncture, the more political favor garnered by the claimant. The prevailing political background of this time reduces the credibility and acceptance of many of the developments in the field, and the numbers of successful applications of acupuncture that were claimed to have been accomplished by Chinese medical institutions during this time period.

In July, 1971, during a visit to Peking, James Reston, an editorial columnist and vice president of the *New York Time*s, required an emergency appendectomy. His Chinese doctors used acupuncture for the treatment of his post-operative pain. This marked the first time an American had been treated by acupuncture in China [Ref. 2:p. 10]. The American public and the scientific and medical communities were fascinated by the acupuncture reports and wanted to know more. In 1972, President Richard Nixon made the first official visit to China by a Western dignitary since the Communist Revolution. The doctors and reporters who accompanied President Nixon were amazed by the phenomenon of acupuncture as they were led on official tours. The stories of their experiences were quickly relayed back to an equally enthralled, but skeptical, audience in the United States. The National Institute of Health (NIH) began to offer grants for the purpose of investigating the workings of acupuncture. The National Academy of Science (NAS) commissioned a panel of its members to go to China on a fact-finding mission. Dozens of books "explaining" acupuncture to the layman were published. "Acupuncturists" began to offer their services all across America.

The novelty of acupuncture wore off after a couple of years. The NIH grants were discontinued. Most of the research performed during that time period simply resulted in a large body of anecdotal evidence that acupuncture indeed worked, with varying degrees of success, on some patients, for some conditions, at some

times. After the initial furor subsided, increasing numbers of serious researchers and medical doctors, especially those associated with university hospitals, began methodical study of the phenomenon. Other modern countries also began to study the topic seriously and incorporate it as a complement to other modern medical methods. In France and Japan, acupuncture is much more widely practiced than it is in the United States. Japan is the world leader in the development and use of electro-acupuncture. The fact that acupuncture works is now widely accepted by Western scientists, doctors, and public, despite disagreement of the exact method by which it achieves its effect.

C. METAPHYSICAL UNDERPINNINGS OF ACUPUNCTURE

The traditional Chinese explanation for the phenomenon of acupuncture involves the concept of a fundamental life force, called *Qi* or *Ch'i*. This life force is thought to circulate throughout the body in conduction paths or vessels known as *meridians*. It is believed that the disturbance of the flow of qi is responsible for all physical ailments and pain. The stimulation of *points* along the meridians is supposed to restore the proper flow of qi.

There are 26 main meridians. These consist of 12 *paired* and two *unpaired* meridians. Sometimes these are referred to as the 14 main meridians, considering each of the 12 pairs to be a single meridian. The paired meridians are roughly symmetric with respect to the *median* (divides the body into left and right halves) plane. The two unpaired meridians are the *conception* meridian and the *governing* meridian, which run down the *ventral* (front) center and *dorsal* (rear) center of the body, respectively. There are many branches and auxiliary meridians, but the 26 main meridians are far and away the most important. Figure 2.1 is a rendition of the paths of the main meridians throughout the body.

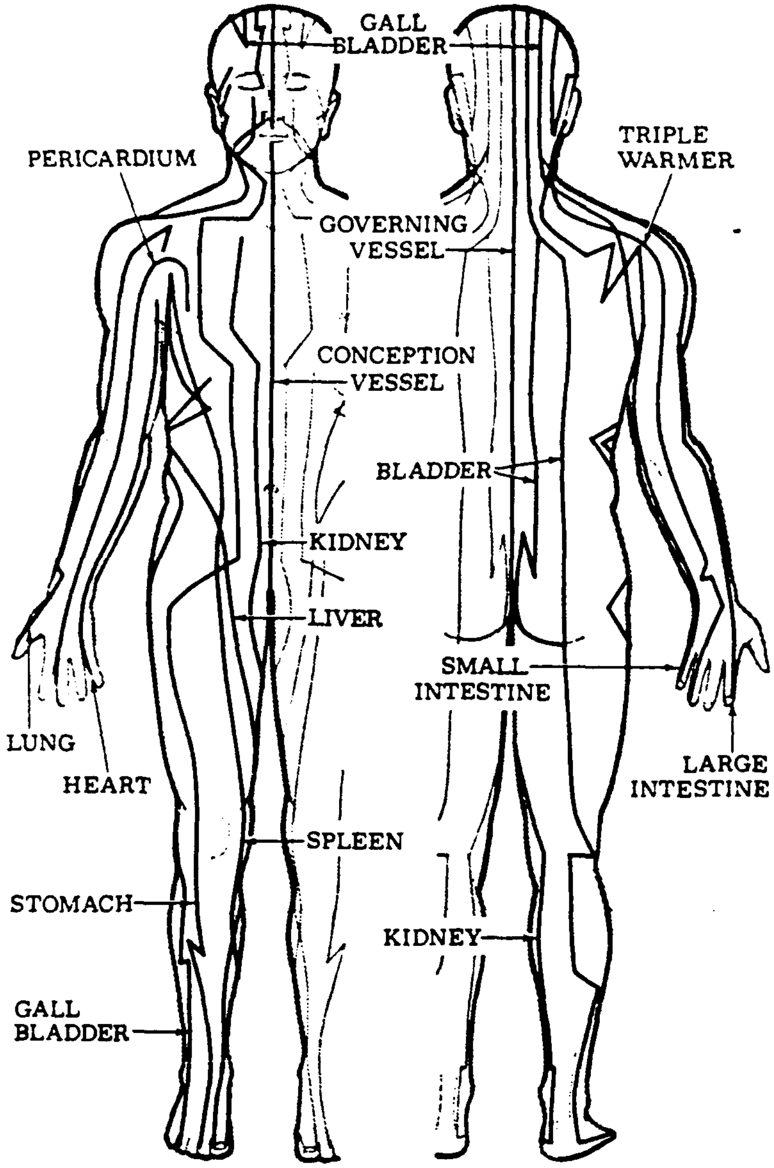

Figure 2.1 The main meridians.
The figure is from Ref. 3:p.36.

In addition to providing circuits for the flow of qi, the meridians serve to connect *viscera* (internal organs) to specific points along the skin. The flow of qi through those points controls the health of that body component. Physical ailments are caused by either an over-accumulation of or a lack of qi at a point associated with the body component. The acupuncture points are stimulated, usually with sharp metal needles, to stimulate or reduce the flow of qi through the point.

The meridians are named for the major *organ* to which each meridian provides the flow of qi. However, some organs, such as the *triple heater*, are unknown to Western medicine. The points might not be anywhere close to the physical location of the body component. The points are named for the meridian on which they lie and for their sequential location along that meridian, numbered inward from the periphery of the body. Over 1000 points are known and catalogued, but many are redundant. Almost all points are repeated on the soles of the feet and in the vicinity of the ears. Figure 2.2 depicts the Large Intestine meridian (located in the left arm) and highlights the acupuncture points it contains. There are twenty points on this meridian. The points are numbered sequentially from the outermost part of the body towards the center of the body. The inset shows that the meridian crosses over the shoulder to pass through point *Large Intestine 16*, or more commonly, *LI 16*. Also note the point LI 4, at the base of the thumb; it will be discussed later.

Figure 2.2 The Large Intestine meridian.
The figure is from Ref. 4:p. 45.

Qi circulates at a different level of activity in each of the meridians throughout the day. There is a peak level of activity for a two hour period, followed by a two hour period of minimal activity, in each of the meridians in turn. An acupuncture treatment is much more effective if it is performed with regard to the rhythmic level of qi. If an ailment is caused by an excessive accumulation of qi at a point, the acupuncture treatment should be applied during the peak level of activity of qi in the associated meridian to disperse the excess energy.

D. ACUPUNCTURE PRACTICE

The main idea (and intrigue) of acupuncture is that the stimulation of a point far removed from the troubled part of the body will induce a calming sensation,

reduce pain, or cure a diseased visceral organ. Acupuncture treatments are performed by the stimulation of the acupuncture points by some method. Scores of methods (and scores of variations on each of those) are used to stimulate the points with varying degrees of success. The method which is employed is *not as important* to the achieved results as is the application of the *stimulation exactly at the acupuncture point*, not just near it.

The stimulation is usually sustained for about 20-30 minutes before any effect is noticed, e.g., an increase in pain tolerance. The effect reaches a peak, then levels off. The effect can be sustained at this level for one to two hours by the application of intermittent stimulation every 20-30 minutes. After this time, more frequent and intense stimulation of the point is needed to sustain the effect. The effect usually cannot be sustained after about four hours, regardless of the magnitude of the stimulation. Once stimulation has stopped, the effect diminishes at a rate of about 50% of its previous level every 15 minutes, so that the effect is essentially gone after one hour.

1. Needles

The most common method used to stimulate an acupuncture point is with a fine metal needle inserted a few millimeters through the skin. After insertion, the needle is manually manipulated, supplied with electric current, or heated. Sometimes these techniques are combined to achieve an increased effect. Five to ten millimeters is a common depth of penetration when acupuncture is used as anesthesia. However, different depths of penetration are used by different practitioners. The object to be stimulated is not very well defined. Some acupuncturists try to hit the motor end plates (where neurons terminate on muscle fibers,) others the underside of the skin, and others any subcutaneous tissue.

Many practitioners believe they are simply inserting the needle into a point on a meridian, despite the fact that no physical evidence of a meridian as an anatomical structure has ever been found. The insertion of needle is supposed to bring on the *de qi* sensation; localized numbness, heaviness, unpleasantness, and swelling, but not pain. In fact, acupuncturists specifically avoid inducing pain at the site. This is significant as it reduces the likelihood of the *gate theory* of the acupuncture mechanism. Acupuncturists claim to detect a sensation as if the needle had been grasped by a muscle when the *de qi* sensation is produced [Ref. 5:p. 19]. Usually, two to four needles are used and stimulated alternately, for a treatment .

Acupuncture needles are solid, very thin, and usually between one and two inches long. Some points on branch meridians are deep within the body; on the periosteum of the femur, for example. Consequently, some needles are up to eight inches long. Some needles are so thin that they must be guided by glass sleeves held against the skin to prevent their bending as they pierce the skin. Acupuncture in ancient times was performed by probing the skin with sharp flints of stone. The stone needles used in ancient times were replaced with sharpened bits of bone or bamboo, then by gold and silver wires. Today, acupuncture needles are usually made of stainless steel, as are most modern surgical implements. Stainless steel is strong, economical, and easily sanitized. However, disposable needles are being more commonly used in light of the AIDS epidemic.

a. Manual Manipulation

Manual manipulation of the needles is obviously the cheapest and least complicated type of treatment to perform. Pumping the needle up and down about three or four millimeters, twirling the needle clockwise then counter-clockwise through a rotation of approximately one circle, or a combination of the

two motions are examples of possible manual manipulation methods. Different manipulations are used to achieve different effects for different treatments, even at the same acupuncture point for the same organ. Manual manipulation of the needle is usually performed at a frequency of two to four times per second. The magnitude of the stimulation that is achieved can be increased by:

- the use of a larger diameter needle
- deeper insertion of the needle
- increased motion of the needle to cause increased localized trauma
- the use of needles with blunt or hooked ends
- the use of more acupuncture points that have similar effects
- leaving the needle in place for longer times
- repetition of the treatment at frequent intervals

However, increased stimulation of an acupuncture point will not necessarily increase the desired curative effect, just as an increased dose of a prescribed drug will not necessarily increase the effect on a particular patient.

b. Electrical Stimulation

Electrical stimulation of the acupuncture points is rapidly becoming the predominant method of performing acupuncture treatments. It seems to be more effective than manual stimulation of the points and is much less labor intensive. (Major surgery, such as the removal of a lung, might require ten needles in each hand and foot, and the coordinated efforts of four acupuncturists to manually stimulate all the needles.) The acupuncturist can insert the needles, attach the electrodes from an electrical stimulator, adjust the settings, and then simply monitor the state of the patient. Simple and cheap electrical stimulators are

now readily available in all countries in which acupuncture is practiced. The stimulators usually have adjustable voltage levels; from one-quarter volt to as much as 50 volts. Different stimulators generate different waveforms; sine waves and bipolar and unipolar pulse trains of varying width pulses are common. A typical pulse width is in the tens of milliseconds. The frequency of the waveform usually can be adjusted between DC and about 250 Hz. A treatment typically begins at a frequency of two to four Hz; the same frequency as that used for manual needle manipulation. The acupuncturist typically adjusts the voltage and frequency of the stimulator several times during a treatment session. For example, when electro-acupuncture is used as analgesia for an operation, a 3 Hz signal might be used for 20 - 30 min. to induce a calming sensation, then the frequency increased to 50 Hz just before an incision is made.

c. *Moxibustion*

This variation of acupuncture is believed to be almost as old as acupuncture, based on historical writings. *Moxa,* a gummy material made from leaves of mugwort (*Artemisia vulgaris,*) is placed on the end of an acupuncture needle previously inserted at an acupuncture point and lighted. The heat generated from the burning moxa is conducted down the metal needle into the acupuncture point to provide additional stimulation of the point. The moxa may be rolled into a small cigar shape and impaled on the end of the needle. However, special needles with small cups on top are made specifically to hold moxa. Also, small cones of moxa can be shaped and placed directly on the acupuncture point. Regardless of whether a needle or direct application is used, the burning moxa is removed from the patient just as the patient begins to feel the heat to prevent actually burning the skin. Alternatively, some acupuncturists claim to achieve a

similar effect by the application of a cold stimulus at a point, using an implement such as a sharp piece of ice or a chilled metal stylus.

2. Other Stimulation Methods

Acupressure is the manual stimulation of the acupuncture points by finger pressure (*Shiatsu* in Japanese). Shiatsu has developed as a separate but related art. Shiatsu has been practiced for centuries in the Orient as a home remedy because of its simplicity and because no equipment is needed.

Reflexology, also known as zone therapy, is the practice of manual massage of the soles of the feet. It has been found to be effective in restoring good health, and claims have been made that it has been used effectively as anesthesia for operations. Reflexology has its own system of conduction paths between the internal organs and the soles of the feet, called *reflexes.* However, reflexology is a much less studied and practiced art. Almost all the acupuncture points are repeated on the soles of the feet. Therefore, reflexology probably is just the practice of acupressure using only points on the soles of the feet.

Acupuncture has been successfully performed using infrared lasers in university hospitals [Ref. 6:p. 122]. The laser beam causes a thermal effect on the surface of the skin to stimulate the point. Laser acupuncture is expected to be tremendously useful in veterinary medicine. Written records and acupuncture charts indicate that acupuncture has been used on horses and cattle for thousands of years. However, the animals usually do not want to be stuck with needles. Therefore, laser acupuncture should be useful in the treatment of children and squeamish adults also.

Some physical therapy treatment techniques have been adapted to provide stimulation of the acupuncture points. Ultrasound therapy uses acoustic

vibrations at frequencies above the range of human hearing. When ultrasound is used to stimulate acupuncture points, an electric current is passed through a piezoelectric crystal placed on the point. The vibration of the crystal causes localized heating and mechanical massage of the point, but may also have a direct effect on subcutaneous nerves.

High frequency (HF) electromagnetic radiation (3 MHz - 30 MHz) is also used to raise skin temperature at a point. The signal is usually pulsed to allow dissipation of heat. *Diathermy* uses higher frequencies, around 27 MHz, to produce the effect deeper within the body to stimulate a deep acupuncture point. Low-frequency currents (< 100 Hz) are rapidly attenuated by skin resistance and cannot reach deep within a limb unless the magnitude of the current is raised to an undesirable level. *Interferential therapy* uses two higher frequency currents (~ 5 kHz) applied to the skin to form a lower beat frequency (~ 100 Hz) deeper within the body, akin to using a long needle to stimulate a deep acupuncture point.

E. REALITY CHECK - WESTERN ACCEPTANCE

1. Acupuncture Does Cure Many Ailments

Many Western doctors and scientists now agree that acupuncture does provide an effective treatment of many ailments, generally those with no organic causes. However, the treatment often needs to be repeated frequently, or even semi-continuously. Acupuncture will not heal lesions, nor will it kill germs or bacteria. However, acupuncture will increase the energy level of the body so that the body can better fight germs, bacteria, or combat the causes of an organic disease. Also, it can provide temporary relief from the symptoms of an ailment. Acupuncture is considered to be especially good for the treatment of:

- headaches and ulcers
- allergies, asthma, and bronchitis
- digestive problems and liver ailments
- arthritis and rheumatism
- high blood pressure
- depression and anxiety
- sexual dysfunction

2. Acupuncture Does Induce Some Degree of Pain Relief

For a treatment to be medically classified as anesthesia, it must totally abolish all sensation. Since patients undergoing acupuncture remain fully conscious, alert, and attentive, acupuncture anesthesia is more accurately referred to as acupuncture *analgesia*. Analgesia is a reduction of the pain experience.

Before using acupuncture as the primary analgesia for an operation, doctors perform a suitability analysis on the patient. This examination determines the degree of apprehension, willingness, and fear of needles of the patient. Also, a test for the *de qi* response at an acupuncture point is performed. Most often, this test is performed at LI 4, which was noted on Figure 2.2. Studies of hundreds of thousands of these interviews have been performed. Analysis of these studies show that only 15% of the population is amenable to acupuncture analgesia. Furthermore, acupuncture analgesia has been found to work on only two-thirds of that fraction of the population. Western doctors hope to increase the number of people for whom acupuncture works by augmenting the acupuncture mechanism once it is found.

3. Meridians and Acupuncture Points Exist

The existence of both meridians and acupuncture points is readily verified in live patients with electrical test equipment. Low electrical resistance points (LERP) appear on the skin at times of corresponding visceral ailments. Also, when a point in a meridian is stimulated, the resistance decreases all along that meridian, allowing the meridian to be mapped. The routes of the meridians as determined by resistance measurements agree with those provided by traditional acupuncture knowledge and charts. Electrical measurements also verify the position of all acupuncture points (over 1000) and that almost all points are replicated in the vicinity of the ears and on the bottom of the feet. In fact, the use of electrical measurements has been the primary tool used in the determination of the redundancy of many points and in the subsequent reduction in the number of points used by contemporary acupuncturists.

However, neither meridians nor points can be found by electrical measurements on dead people or animals. Also, no *physiological artifacts*, that is anatomical structures, of meridians have been proven to have been found. Many searches and claims of success have been made, but the *discovered* structures are usually attributed to *histological artifacts,* that is, remnants of body tissue on the microscope slide due to sloppy lab procedures.

III. CONVENTIONAL NEURAL THEORY

The fundamental functional unit in the nervous system of any animal is the *neuron*, or nerve cell. In simple organisms, the few nerve cells (less than 200 for a roundworm), are homogeneously distributed in a network throughout body. In more advanced organisms, the cell bodies of the neurons are clustered together in groups called *ganglia*. In this configuration, a multitude of inter-neural connections exist, which permits rudimentary information processing. Ganglia are the precursors of the brains of more advanced animals, in which as many as 10^{15} interconnections may exist (human brain.) In a human, the neurons that comprise the brain and spinal cord are collectively known as the *central nervous system* (CNS). Neurons in the outer reaches of the body are collected into groups by connective tissue to form *nerves*. Nerves form the *peripheral nervous system* (PNS), which transmits information to or from the brain and spinal cord.

A. NEURON PHYSIOLOGY

Nerve cells vary between 5 - 100 μm in diameter, but can be very long. In fact, neurons are the longest cells in the body of any animal and can reach a length of two meters in some large vertebrates. A neuron consists of a *soma* (body) and one or more *processes* surrounded by a common cell membrane. The soma contains components common to any cell; the nucleus, cytoplasm, mitochondria, etc. A process is an extension of the cell body; it consists of the cell membrane and cytoplasm. Each process is an electrical *hookup point*. The number of processes is equal to the number of electrical poles of the neuron. There are two

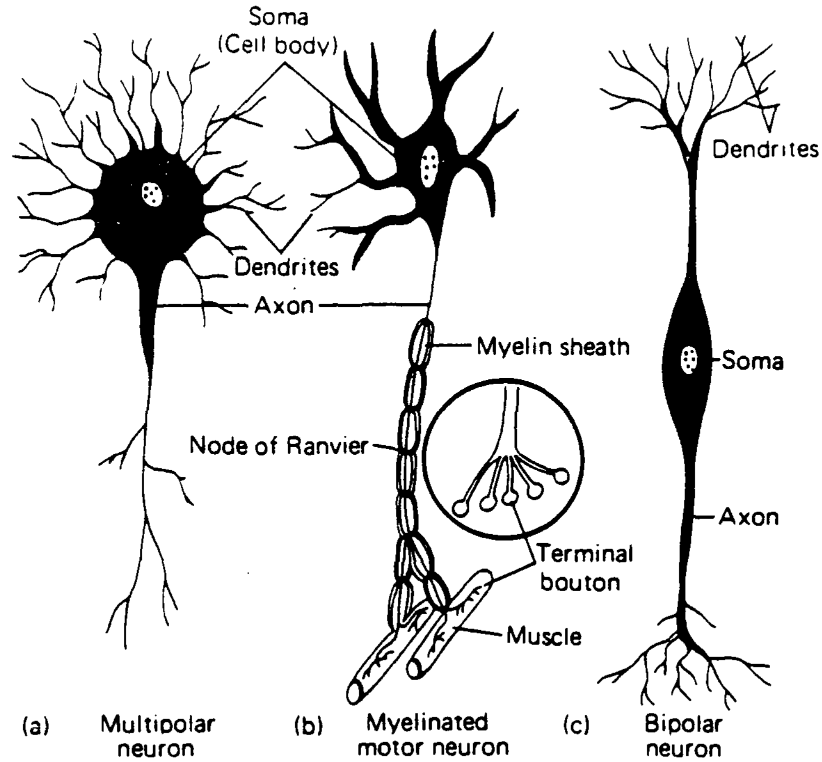

Figure 3.1 Different types of neurons and their components.
The figure is from Ref.7:p. 507.

types of processes, *dendrites* and *axons*. Three of the more common neuron types are shown in Figure 3.1.

Dendritic trees, or dendrites, are short branching structures that receive inputs to the cell and forward those inputs to the soma. The other areas of the membrane of a nerve can receive electrical input also, however, the vast majority of the inputs to the cell are hooked up to its dendrites. There are usually many; about 100 for a typical human neuron. They have high internal resistance, and are prone to surface leakage of current.

An *axon* is a long, constant-diameter process that conducts the nervous impulse away from soma. The larger the diameter of the axon, the lower its internal resistance per unit length and the higher the propagation velocity of its nervous impulse. Thus the thickest axons are those which function in the *escape*

reactions of some invertebrates, such as squid and cockroaches. The end of the axon is usually branched to allow the output of the neuron to be connected to many (about 5,000 - 10,000) other neurons.

The above description is for the most common type of neuron; the *multipolar* neuron, renditions of which appear in Figures 3.1.a and 3.1.b. In a *bipolar* neuron, Figure 3.1.c, all dendrites connect to a single constant-diameter *peripheral process* that conducts the input signal over the remaining distance *to* the cell body. Bipolar neurons are found in the retina. A *central* process is similar to an axon, and conducts the output away from the soma. In the bipolar nerve cell, the peripheral and central processes function as electrically separate poles, respectively conducting the input toward, and the output away from, the soma. In the *unipolar* cell, the input and output processes are shorted together at the junction with the soma, forming a *wire*, or single pole.

Axons often become insulated by the process shown in Figure 3.2. *Schwann cells*, which are a type of *Glial cells* (both names are for the discoverers) migrate to a neuron and wrap themselves around the axon (Figure 3.2.a). The Schwann cells then travel around and around the axon, leaving their cell membranes, but almost no cytoplasm, in place as they orbit the axon (Figure 3.2.b). The multiple layers of cell membrane that remain in place around the axons are known as *myelin* (Figure 3.2.c). Myelin is a fatty substance with a high electrical resistance. It serves to insulate the axon and significantly increase the rate at which the nervous impulse is conducted. In fact, nervous impulses in some of the largest diameter unmyelinated axons, such as those found in the giant squid, have a propagation velocity of 20 m/sec. However, the smaller, *but* myelinated, axons in mammals can support impulse velocities of 100 m/sec. Schwann cells are about

1 mm long. Small gaps, known as *Nodes of Ranvier,* occur between the Schwann cells, uncovering the cell membrane at those nodes. The Nodes of Ranvier are shown in Figure 3.1.b.

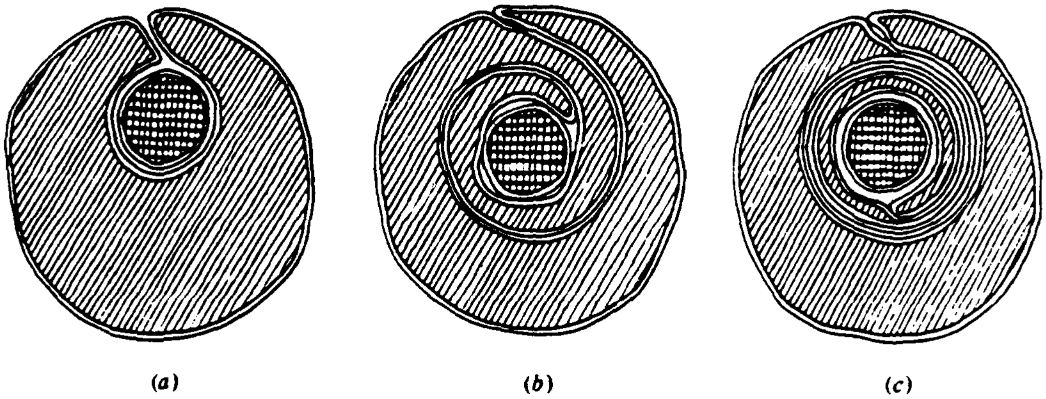

Figure 3.2. Schwann cell growth. The figure is from Ref. 8:p. 4.

Neurons are classified not only by their physical configuration, or by their number of poles, but also by their function. *Afferent* neurons are sensory neurons. They connect signals *from* receptors, such as for tactile or temperature sensation, *to* synapses in the central nervous system (CNS).

Efferent neurons, also known as *motor* neurons, receive inputs *from* electrical junctions in the CNS and conduct signals *to effectors*, e.g., muscles and endocrine glands. At a neuromuscular junction, the axons of motor neurons terminate in *motor end plates* on the cell membrane of muscle cells. An electrical impulse conducted by the neuron causes chemical changes in the membrane of the muscle cells, which causes the muscle to contract. *Somatic* motor neurons terminate on musculoskelatal structures of the limbs or skin, or on *fascia*, connective tissue which binds together parts of the body. *Automatic* motor neurons are connected to

glands and to smooth muscle found in *viscera*, internal organs and structures. In addition to functioning to stimulate the endocrine glands, some efferent neurons secrete hormones of their own, called *neurohormones*; a phenomenon known as *neurosecretion.* During times of stress, the amount of *noradrenalin* (a neurosecretory substance), produced by motor neurons is almost as much as the amount of adrenaline released into the circulatory system by the endocrine glands.

Association neurons, also known as *interneurons*, serve to make connections between other neurons, especially in the brain and spinal cord. A single interneuron may serve to connect a simple *reflex arc,* in which the signal from an afferent neuron triggers an efferent neuron to trigger a muscle response directly, without any further processing by the CNS. An interneuron might serve to integrate many sensory inputs and connect the resultant signal to higher centers for processing.

B. THE SYNAPSE

The ends of most axons branch out so that the output signal from that neuron is connected to thousands of other neurons. Each branch of the axon terminates in a *synaptic knob*, or *terminal bouton*, which is the connecting structure between an axon branch and a receiving neuron. Most synaptic knobs terminate on the dendrites of the receiving neuron, however, some terminate on the soma or axon of the receiving neuron. Figure 3.3 illustrates the arrangement and components of a synapse.

The synaptic knob is a bulbous shelter around the region of connection to the next neuron (~ 1 μm diameter.) It contains cytoplasm, mitochondria, and *vesicles*, which are small (~ 30 nm diameter) sacs of *neurotransmitter*. The synaptic knobs of neurosecretory neurons also contain *secretory granules*, which are large

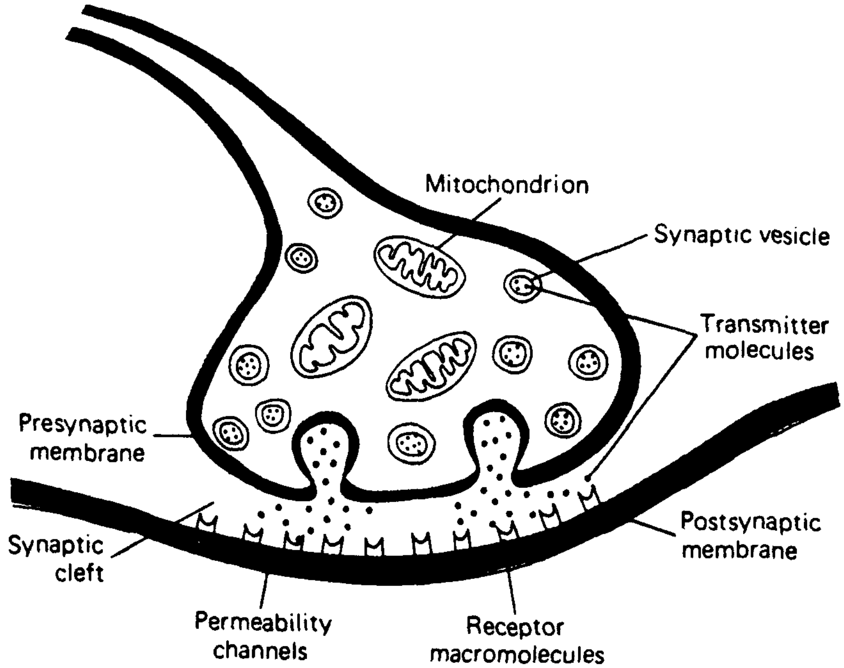

Figure 3.3 A synapse. The figure is from Ref. 7:p. 514.

vesicles which contain and secrete neurohormones. It is important to note that the knob does not make physical contact with the next neuron; the two structures are separated by a small (~ 20 nm) gap of intercellular fluid called the *synaptic cleft.* During transmission of the nervous impulse, neurotransmitter must diffuse across this gap, which significantly increases the propagation time of the signal.

The chemical identity of the neurotransmitter marks a limit of the current level of knowledge about the neural transmission process. About 50 substances have been identified, but any number more could exist. The identities of each known neurotransmitter were deduced from observing which of various chemicals injected into a synapse prevented the neurotransmitter chemical from functioning properly. Acetylcholine, noradrenalin, and Substance P are neurotransmitters that have been identified in synapses both inside and outside the CNS. Serotin,

dopamine, glutamate are neurotransmitters that have been found only in synapses outside of the CNS.

C. TRANSMISSION OF THE ELECTRICAL IMPULSE

The electrical current known as the nervous impulse is not a flowing stream of electrons. Instead, the *current* is actually a movement of a temporary, localized change in the voltage gradient across the cell membrane moving down the length of the neuron with respect to time. The local changes in voltage gradient occur as the result of diffusion of ions into and out of the cell, which in turn is due to a change in the permeability of the cell membrane in response to a stimuli.

1. The Resting Potential

The cytoplasm of the neuron is filled with many positive and negative ions. The cell membrane is selectively permeable to all the positive ions, the majority of which are sodium (Na^+) and potassium (K^+) ions. Most of the negative ions are long-chain protein molecules that are too large to fit through permeability channels in the cell membrane. An exception is the chloride (Cl^-) ion, which is able to diffuse through the cell membrane. A *sodium-potassium pump* pumps sodium out of, and potassium into, the cell. Potassium has a higher ionic conductance than does sodium. That is, the selectively permeable membrane allows potassium ions to diffuse outward through the membrane more easily than it allows sodium to diffuse inward through the membrane. The result is a net increase in sodium concentration, and a net positive charge, outside the cell. When the combined effects of the pump, the different diffusion rates, the exterior sodium concentration and the internal potassium concentration are in balance, the interior of the cell is electrically negative to the exterior of the cell by about 70

mv. This potential difference across the cell membrane is the *resting potential,* or *resting membrane potential*, of the cell.

2. The Local Response

Electrical input signals from transmitting neurons are received across synapses by the dendrites of the receiving neurons. The reception of stimuli causes permeability channels in the cell membrane of the receiving neuron to alter in one of several ways. Excitatory stimuli increase the permeability of the cell membrane to sodium. A subsequent inrush of positive sodium ions reduces the magnitude of the negative voltage difference across that region of the membrane. This change to the value of the resting potential is known as the *excitatory postsynaptic potential* (epsp). The inrush of sodium has a circular interaction with the membrane; the reduction of the voltage gradient due to the sodium inrush further increases the permeability of the membrane to sodium, which causes further inrush of sodium, etc.. The localized change in membrane potential, the *local response*, is proportional to the logarithm of the intensity of the stimulus.

Some of the sodium ion inflow diffuses to adjacent areas, which affects the permeability of those areas. Subsequent sodium inflow changes the voltage gradient of these adjacent areas, but in a diminished manner since the sodium inflow is not as great as it is at the site of stimulation. Therefore, the epsp propagates spatially, but attenuates as it does so. The local response due t· a weak stimulus dies out quickly After the sodium ion inflow, the change in the voltage gradient increases the permeability of the cell membrane to potassium. Potassium ions flow out of the cell, restoring the voltage gradient to its normal value in the area of the original stimulus.

3. The Nervous Impulse

Dendrites and soma perform spatial and temporal summation of the received stimuli. When the sum of local depolarizations reduces the magnitude of the voltage gradient across the cell membrane to about 70% of its resting potential, the voltage gradient across the cell membrane will reverse polarity, to a maximum value of about +30 mv. The depolarization will become self-propagating and spread across the cell membrane and down the axon. The value of the membrane voltage gradient at which this occurs is called the *threshold voltage* of the neuron; that level of depolarization needed for the neuron to respond to the stimuli. The resulting change in voltage along the length of the axon with respect to time appears to be an electrical impulse moving with a rapid pulse speed and is known as the *nervous impulse* or *action potential.*

The time-voltage history of this pulse is shown in Figure 3.4. The rise time of the impulse, between 0.5 - 1.0 sec. is the *absolute refractory period.* A new nerve impulse cannot be triggered during this period, regardless of the magnitude of the stimuli applied to the neuron. The fall time of the impulse, and the time of restoration of the resting potential, is the *relative refractory period.* A new nerve impulse can be triggered during this period, if the stimuli applied to the neuron is sufficiently large. The absolute refractory period makes the action potential propagate in only one direction. As the action potential moves, and depolarizes, the next adjoining segment of the cell membrane, more sodium will rush into that area of the cell. As the sodium diffuses to adjacent areas, it will trigger more depolarization in all directions. However, since the area behind the pulse is in its

absolute refractory period, that area will be unable to fire again. Thus, the action potential can propagate only in one direction.

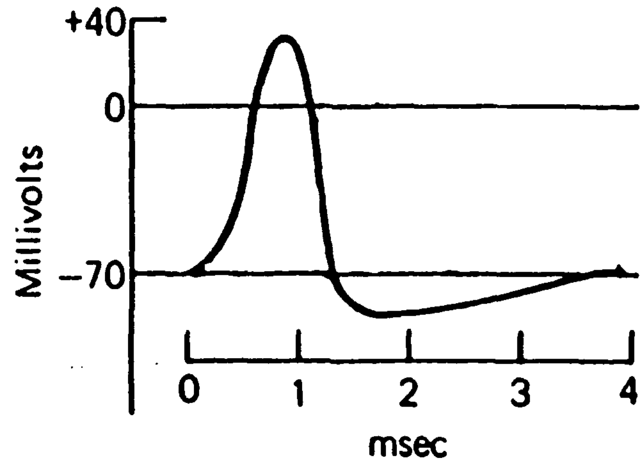

Figure 3.4 Voltage vs. time for the generation of the action potential. The figure is after Ref. 7:p. 512.

As the electrochemical impulse travels down the *pre-synaptic* (on its way to the upcoming synapse) axon, the high-resistance myelin sheath (from the Schwann cells) around the axon prevents current from leaking through the cell membrane. At the next Node of Ranvier (every 1 - 2 mm), the action potential will depolarize the exposed cell membrane, reach threshold, and trigger a new action potential. The phenomenon of the nervous impulse regenerating the original signal at the next node it reaches is called *saltatory* (jumping) conduction.

When the action potential reaches a synaptic knob, the synaptic vesicles in the knob move toward, and merge with, the presynaptic membrane. Small quantities (3 - 1000 molecules) of neurotransmitter are ejected into the synaptic cleft from each of these vesicles, travel across the cleft, and combine with receptor molecules in the postsynaptic membrane. The receptor neuron becomes

chemically excited. Its postsynaptic membrane depolarizes and the process repeats in this neuron as in the previous one.

Receptor neurons can become chemically inhibited (*hyperpolarized*; the cell potential moves further from zero), by the action of neurotransmitter. In this event, the membrane becomes increasingly permeable to potassium (instead of sodium), which results in an outrush of potassium, which increases the magnitude of the cell voltage gradient to 80 - 90 mv. The minus10 mv change in the cell voltage gradient is called the *inhibitory postsynaptic potential* (ipsp). Alternatively, the inhibitory neurotransmitter may cause the postsynaptic membrane to become increasingly permeable to chloride. The subsequent inrush of chloride also increases the magnitude of the voltage gradient to 80 - 90 mv. In either case, the larger voltage gradient prevents the normal outward diffusion of potassium until normal inward sodium diffusion restores the resting potential of the neuron.

Only one neurotransmitter has been found at any one synapse. However, the same neurotransmitter may activate excitatory receptors, or inhibitory receptors, or both, in the same postsynaptic membrane. After use, neurotransmitters are resorbed by the presynaptic membrane or broken down by enzymes. If the neurotransmitter remained in the synapse, it would continue to stimulate the receptors in the postsynaptic membrane, which would cause muscle spasms and death in the organism. For example, many insecticides and nerve gases work by interfering with the action of acetylcholinesterase, an enzyme that breaks down acetylcholine, a neurotransmitter [Ref. 7:p. 517].

D. THE GAP JUNCTION

The preceding discussion pertained to the most common type of nervous impulse conduction, that occurring at the chemical synapse. Another type of neuron connection has been proven to exist, the *electrical synapse*, or *gap junction*. At this connection, current is coupled across a small (~3 nm), low-resistance region between neurons. Since no diffusion of a neurotransmitter is involved, this type of synapse allows for faster transmission of the nervous impulse and allows two-way signal flow.

E. INFORMATION CODING

There is little understanding of the manner in which the nervous system transmits and processes a wide variety of information. The information coding ability of the nervous system seems very limited since the nerve impulse, or action potential, of a particular neuron is always of the same magnitude and duration. Pulse-frequency modulation, control of the number of action potentials in a *burst*, phase coding, and the use of specific neural circuits are some coding schemes that are thought to be used by the nervous system, although the details of the manner in which they are used are unknown.

The nervous impulse frequency is proportional to the log of the intensity of the stimulus, as shown in Figure 3.5. A weak stimulus causes a neuron to fire a few impuses per second, a strong stimulus causes a neuron to fire many impulses per second. An upper limit exists for the frequency of impulses since a neuron cannot be made to fire again during its absolute refractory period, regardless of the strength of the stimulus. The absolute refractory period varies between 0.4 and 2.0 msec for human nerve fibers, establishing a high frequency limit of between 500 and 2500 impulses per second. A weak stimulus cannot cause a neuron to fire

during the relative refractory period, which adds about 2-3 msec to the total length of the refractory period. This total time corresponds to a maximum frequency of about 200 - 250 impulses per second from a neuron experiencing a weak stimulation. These calculations yield the theoretical upper limits. Actual bandwidth for neurons has been determined experimentally to be 50 -200 Hz.

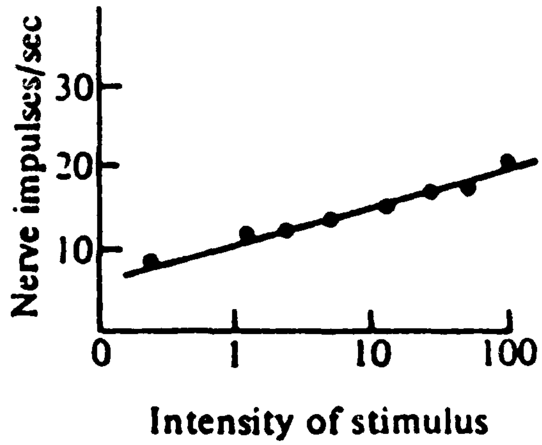

Figure 3.5 Impulse frequency vs. strength of stimulus.
The figure is from Ref. 8:p. 17.

The magnitude and duration of the stimulus also controls the total number of impulses that occur during a *burst*. The duration of the burst can be considered as a single, variable length bit. Any utilization of this method of encoding is unknown.

Another possible encoding scheme is phase coding. In this scheme, the difference in the arrival time of bursts from different upstream neurons is used to convey some information. It is possible that such a method may be involved with processing attention mechanisms by the brain [Ref. 9:p. 274].

A fourth manner of information encoding is established by the wiring or circuitry of the nervous system. Different neurons have different thresholds for firing, and are connected in exact, though usually redundant, sequences and to

different areas of the brain. For example, light receptor cells in the retina of the eyes connect to certain neurons in the brain which control vision. If these cells should fire for any other reason than a stimulus of light, for example, a blow to the head, the brain would still *see* flashes of light [Ref. 7:p. 518]. Although all the neurons of the human body are hard-wired together, these connections can be broken and rewired by the body. Old connections are broken when some axon branches die back, then new connections are made by the growth of new axon branches.

F. ORGANIZATION OF THE HUMAN NERVOUS SYSTEM

The human nervous system has two main physiological parts. The brain and spinal cord comprise the central nervous system (CNS). The CNS is wrapped in *meninges*, layers of membrane, and are awash in *cerebrospinal fluid* (CSF). Interneurons comprise the bulk of neurons in the CNS. The cell bodies of interneurons form the gray matter of the CNS. The myelinated axons of the of interneurons form the white matter of the CNS. In fact, Glial cells account for about one-half of the brain volume.

Physically, the peripheral nervous system (PNS) is comprised of all nerves and peripheral ganglia outside the brain and spinal cord, i.e., outside the CNS. Functionally, the PNS has two parts. The *somatic* nervous system allows conscious or voluntary control of limbs. The *autonomic* nervous system governs regulatory control of involuntary body functions. The automic nervous system consists of only motor neurons, and has two subsystems, the *sympathetic* and *parasympathetic* nervous systems. The sympathetic nervous system controls body functions involved in emergencies, such as heart rate, blood pressure, breathing,

secretion of stimulatory hormones, etc. Parasympathetic motor neurons regulate the operation of many of the same viscera during non-emergency times.

Nerves are bundles of afferent and efferent axons *outside* the CNS. Nerves that project from brain (12 pair) are called cranial nerves. Nerves that project from the spinal cord (31 pair) are called spinal nerves. Note that although these nerves *connect to* the brain and spinal cord, they are *outside* the CNS and therefore, belong to the PNS. All afferent nerves enter the dorsal (back) side of the spinal column; all efferent nerves leave the ventral (front) side of the spinal column. The collective mass of nerves entering or leaving the spinal column is called a *dorsal root* or *ventral root*, respectively. The cell bodies (soma) of PNS sensory neurons form discrete collections in the dorsal root known as *sensory ganglia*. The soma of somatic motor neurons are also located in the spinal cord (for spinal nerves) and brain stem (for cranial nerves) and contribute to the gray matter in these regions. Soma from sympathetic motor neurons are clustered in ganglia in front of the ventral root. These ganglia are cross-connected outside the spinal column so that if any one sympathetic motor neuron is triggered, all will be triggered, even if the normal circuits for the other effectors in the system failed. Their ganglia are located at the effectors that they control. Figure 3.6.a shows the locations of the sympathetic ganglia and the dorsal root (sensory nerves) ganglia.

Reflex arcs are connections between neurons that allow a sensory input to trigger a response, such as a muscle movement, without relying on any higher-level processing. An example is a *monosynaptic arc;* an afferent neuron connected directly to an efferent neuron as shown in Figure 3.6.b. Another example is a *polysynaptic arc*; the inputs from many afferent neurons are

integrated by an interneuron which then triggers a response from an efferent neuron to effect a response.

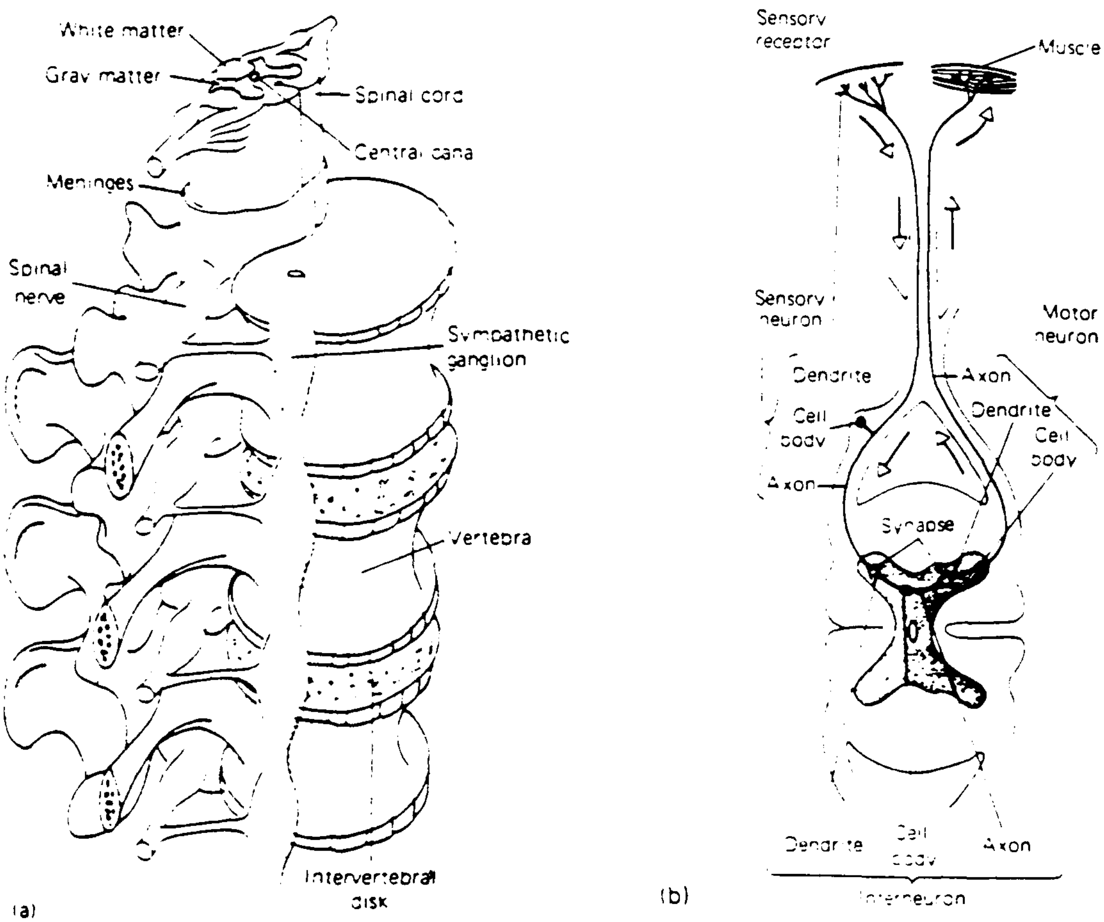

Figure 3.6 Spinal column and reflex arc.
The figure is from Ref. 7:p. 530.

IV. ASPECTS OF ELECTRICAL MODELING

This section deals with the considerations involved with choosing a model to use for the simulation and evaluation of the proposed electrical acupuncture mechanism. The obstacles to the creation of an accurate neural model are imposing. Huge numbers of neural models have been developed and implemented, however, none have been proven to correctly represent biological neuron activity.

One reason it is so difficult to develop an accurate electrical description of a neural system is that there are so many different characteristics of the data stream between the input and the output of a neuron. Neurons seem to behave as analog devices when they initially receive inputs, yet provide essentially digital outputs, i.e., binary pulse-coded sequences. However, the analog portions of the cells have within them some characteristics of digital systems; the digital portions of the cells have some analog characteristics. Obviously, neurons are best thought of as hybrid processors built from both digital and analog components. As models become more physiologically accurate, they become more awkward to implement as the number of neurons in the simulation increases. Alternatively, simple models do not account for important features of neuron behavior.

The second major difficulty in developing a neural model is the difference between individual and ensemble neuron behavior. The element of integration for reception, processing, and transmittal of information is a *local group* of neurons, not a single neuron. The apparent electrical wave form of the group, the *ensemble* electrical response, is different than the unit neuron response. The pulsed inputs to a single neuron are processed according to a sigmoidal shaped transfer function.

In an ensemble of neurons, the transfer function is linear, at least for small to moderate input signal levels. Tne transfer function of the decision to fire an output pulse as a result of the magnitude of the dendritic wave is just the opposite; the number of output pulses an individual neuron produces is a linear function of the dendritic current, but the ensemble response is sigmoidal.

Thirdly, biological neural networks and communication lines consist of redundant paths and multiple circuits. This fact so complicates neural modeling that it is usually ignored. At best, statistical methods are used to weigh other elements of a model to account for unknown inputs and other uncertainties observed in the behavior of biological neurons.

Non-linear effects, such as feedback, oscillation, and chaos, are present in the behavior of biological neurons and neural networks. These phenomena are modeled to a different degree (usually not at all) by different models. These phenomena have only recently been found to occur in neurons; their roles in neuron behavior is not well understood. Thus, experimental attempts to account for them in electrical models have begun only recently.

Electrical models of neural communication also differ with the method of the simulation. They can be in the form of mathematical equations, analog, digital, or hybrid electrical circuits, or computer programs. The particular implementation scheme necessarily affects and restricts the nature of the model.

A. LOCAL RESPONSE

All electrical models of biological neurons represent the fact that dendritic current performs spatio-temporal integration of input signals (sums the amount of local membrane depolarizations over space and time,) but vary widely in the method used to represent this phenomenon. Most models manifest this part of

neuron behavior in an analog fashion, however, since the inputs to the dendrites are mainly binary pulses from presynaptic axons, there is also a digital nature to the behavior of the local response. Also, most models do not consider the role that the stable physical and chemical environment provided by the regulatory systems of the body may play in the electrical nature of the neuron.

Mathematical and analog electrical models attempt to account for dendritic current density, a continuous function. The descriptive equations of these circuits include various resistances and capacitances of the cell membrane and surface leakage current at the dendrites. More complex equations are sometimes used to reflect the fact that the analog values are adaptively adjustable.

The dendrites must deal with information that arrives in the form of pulses; usually, this effect is modeled by calculating a graded response of the cell membrane proportional to the log of stimuli intensity (number of received excitatory pulses minus the number of inhibitory pulses.) The response of the cell membrane is most often modeled simply by the *RC membrane model*, shown in Figure 4.1. The propagation of a local depolarization across adjacent areas of the membrane, on the dendrites or across the surface of the soma can be modeled by linking any number of the RC membrane models in series, as in Figure 4.2. Note the current direction across the membrane is opposite to the direction of the dendritic potential wave. The current is flowing to the site of the stimuli to attempt to restore the resting potential at those points. The previously depolarized area of the previous patch of membrane can be modeled by the shorting of all the capacitance and most of the resistance of that portion of the membrane, as shown in Figure 4.2.

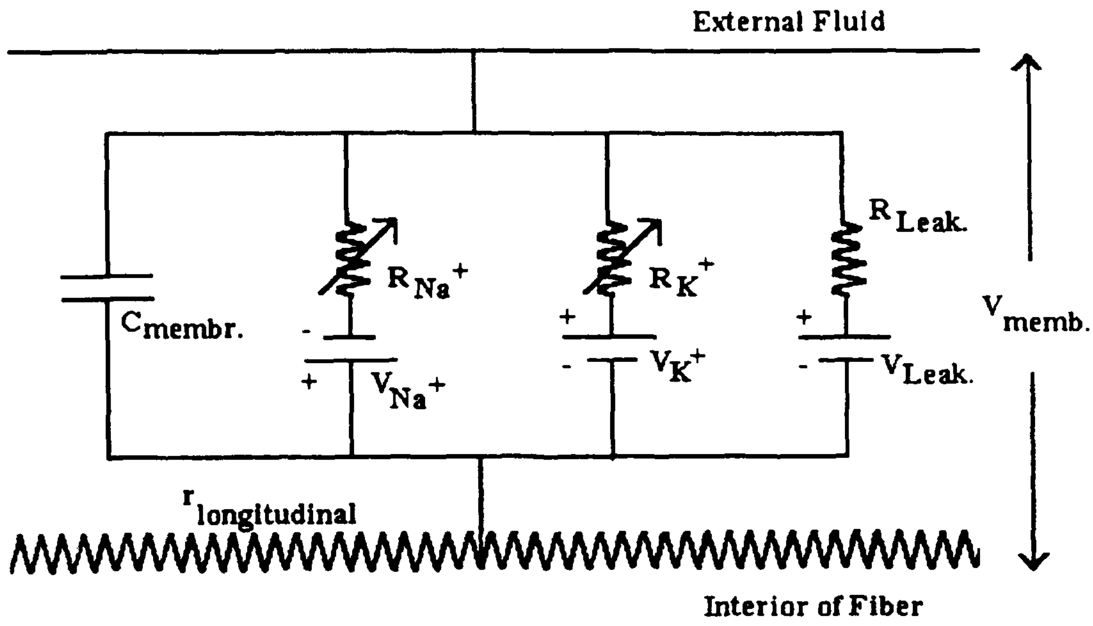

Figure 4.1 RC membrane model. The figure is after Ref. 10.

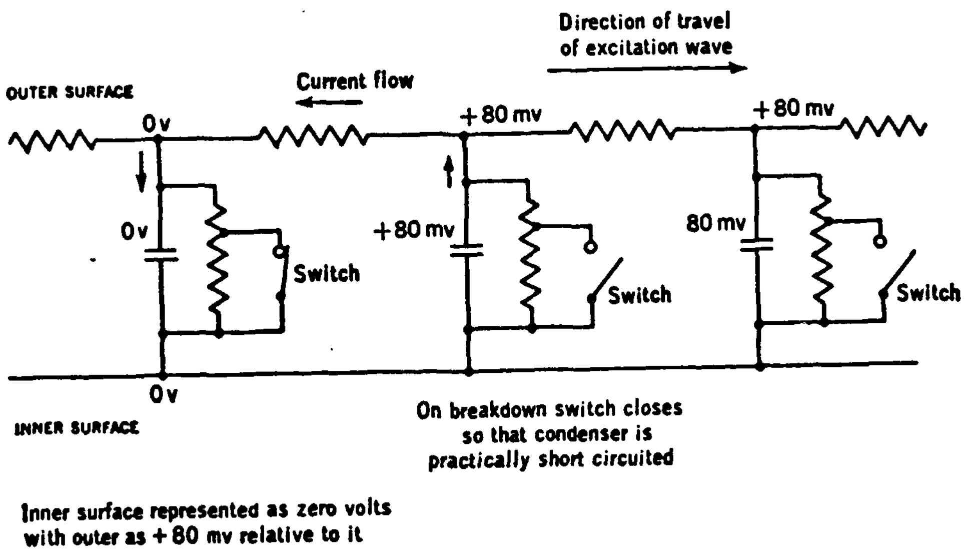

Figure 4.2 Multiple RC membrane models during conduction of dendritic wave. The figure is from Ref. 11:p. 127.

The input resistance of a patch of cell membrane varies proportionately to neuron diameter raised to the 3/2 power [Ref. 12:p.11]. The impedance matching of the dendrite-soma connection can be calculated from the geometric ratio, GR, given by

$$GR = \frac{\sum_{1}^{n} d_i^{3/2}}{d_o^{3/2}} \quad , \tag{4.1}$$

where d_i and d_o are the dendrite diameters for each of n dendrites and the soma diameter respectively. If the geometric ratio is equal to one, impedances are matched across the junction, and the dendritic tree is considered to form an equivalent cylinder with homogeneous electrical properties. If the entire tree is thought of as a single conducting cable, the nature of the propagation of the dendritic wave can be calculated by solving Kelvin's cable equation,

$$\frac{\partial V(x,t)}{\partial t} = \kappa \frac{\partial^2 V(x,t)}{\partial x^2} \quad , \tag{4.2}$$

where V(x,t) is the magnitude of the change of the membrane potential as a function of distance (from the point of stimulus) and time, and κ is a constant which reflects electrical properties (resistance, capacitance, and ion conductance of that portion of the membrane. Solutions to this equation express the amplitude of the dendritic wave as a function of distance and time.

B. ACTION POTENTIAL

Digital circuit models and some computer models load *words* of thousands of bits in parallel, sum the zeros and ones to determine size of dendritic response, and compare it to a preset threshold value. Of course, in biological neurons, the

threshold voltage changes with the history of the neuron. Also, the biological input calculation is not a simple linear addition. Inputs from synapses closer to the dendrite-soma connection (the *trigger zone,*) carry more weight than do those closer to the ends of the dendrites, although there are fewer synapses closer to the trigger zone. Modern implementations add stochastic considerations to improve the realism of model. The number of applied excitatory and inhibitory inputs varies statistically for every cycle of the neuron. The resultant dendritic sum then determines the *probability of emission* of an output pulse. This idea is now being extended to use in hardware implementations; some labs are building *probabilistic RAM* [Ref. 13:p. 299].

After the calculated sum of the local responses exceeds a threshold value, most analog electrical models treat the axon simply as a high resistance output port of the circuit. No effects that occur in the axon, such as circuit loading, time delay, signal amplification, the influence of additional excitatory and inhibitory stimuli, attenuation due to leakage currents, are taken into account. Most of these effects are newly discovered, or are considered to have a negligible effect on the action potential. Hybrid models switch to a digital representation of the neuron at this point, and consider the action potential as a binary pulse.

Digital models treat the action potential as the output pulse of a thresholding logic unit in response a number of pulsed inputs; as

$$y = \begin{cases} 1, \text{ if } (\underline{\underline{w}}^T \underline{\underline{x}}) \geq 0 \\ 0, \text{ if } (\underline{\underline{w}}^T \underline{\underline{x}}) < 0 \end{cases}, \tag{4.3}$$

where x is the input vector of a sequence of ones and zeros, and w is the weight applied to each input, and y is the output pulse. This concept has been used since the early 1940's to electrically represent a neuron. The perceptron is a famous

example. The perceptron is shown in Figure 4.3. Note the manner in which the threshold voltage, x_0, is assigned the fixed value of one, and all input pulses (ones or negative ones, for excitatory and inhibitory,) are weighted with different magnitudes to account for the strength of the input connection. Most Artificial Neural Networks (ANN) use this model. The most significant shortcoming of this model is its inability to account for time delays due to the propagation and summation of the input signals, and generation and propagation of the output pulse. Also, since this model treats all signals as binary pulses, it fails to account for analog considerations, such as attenuation of the action potential. Thus, a hybrid model provides a more accurate representation of a neuron than does a purely analog or purely digital model.

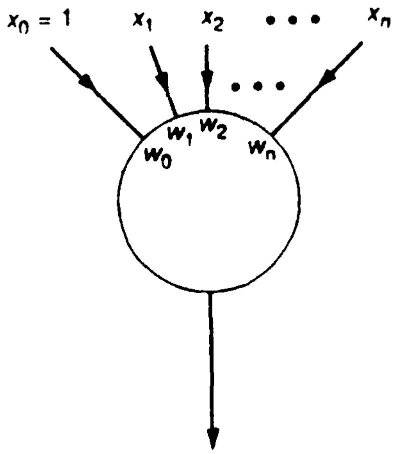

Figure 4.3 The Perceptron. The figure is from Ref. 9:p. 4.

C. NON-LINEARITY

Many non-linear effects are present in the neuron. The active elements in the cell membrane, the voltage-controlled ion conductances, may add or subtract from the input signal, and may therefore result in an oscillatory limit cycle, although only at the local group level, not in single neurons. Also, it is believed that chaos plays a role in the behavior of the neuron. Chaotic phenomena are apparently the cause of what were previously classified as *random* firings of the neurons. This unpatterned activity probably serves to exercise the neurons, to keep them *warmed up*, and to enable rapid state transitions.

The growth of the dendrites was recently found to be described by the same equations that generate some fractals. Additionally, the branching of the daughter fibers from the end of the axon to provide multiple output terminals for the single output pulse, is apparently governed by the phenomenon of bifurcation. A quantitative change in a physical value of the axon branch, i.e., a different membrane resistance or capacitance, causes a qualitative change, i.e., the branching of the previous branch into new branches. It has recently been found that different parent branch / daughter branch junctions have different impedances on either side of the junction. If the geometric ratio (GR) of a particular junction equals one, there is no transmission delay. If GR is between one and ten, a proportional propagation delay exists at the bifurcation point. If GR is greater than ten, there is no propagation beyond the bifurcation point. The GR is fixed for each junction, which implies that different frequency signals propagate through different axon branches.

D. ELECTROTONIC PARAMETERS OF THE NEURON

The term *electrotonic* refers to the altered state of a neuron or nerve during the passage of an electric current through it. Obviously, it is important to know these values as accurately as possible to be able to model the information processing function of neurons. These values are usually obtained directly. A neuron is removed from an animal, and kept alive in an artificial environment (*in vitro*) that is chemically and physically similar to its biological environment (*in vivo*.) Then its various potentials and resistances are measured with micro-electrodes. Other electrical parameters are then determined from the measured parameters. Some measurable properties of the cell membrane are r_i, the longitudinal resistance of the membrane in Ω·cm, r_m, the membrane resistance per unit length in Ω/cm, and c_m, the membrane capacitance per unit length in μF/cm. In more detailed time models, the membrane resistance is measured separately for the soma and dendrites, yielding the parameters r_{soma} and $r_{dendrite}$. Derived electrotonic parameters are:

$$L = \left(\frac{r_m}{r_i}\right)^{1/2} , \tag{4.4}$$

$$R_{input} = \frac{1}{2}\left(r_m r_i\right)^{1/2} , \tag{4.5}$$

and

$$\tau = r_m c_m \text{ (ms)} , \tag{4.6}$$

where L (or λ) is the characteristic (or electrotonic) length of the membrane, R_{input} is the total input resistance of the neuron, and τ is the RC time constant of the membrane. When represented as a single cable, the longitudinal resistance and capacitance of a dendrite form a low pass filter, which can be seen in the RC model of the membrane, Figure 4.1. The resulting bandwidth of the membrane can be calculated directly from the membrane time constant. Some typical electrotonic parameter values for mammalian neurons are listed in Figure 4.4:

R_{input}	85 MΩ
$r_{dendrite}$	120 MΩ
r_{soma}	300 MΩ
L	1 - 10
$\tau_{dendrite}$	10 ms
τ_{soma}	5 ms

Figure 4.4 Typical electrotonic parameter values.

V. PAIN

A. RECEPTORS

The fundamental nature of pain is unknown. A large part of the search for an explanation of the phenomenon of pain has been the attempt to find a discrete physiological structure that detects painful stimuli and then transmits a corresponding electrical message. Usually, such efforts have consisted of tracing afferent (sensory) nerves from the dorsal root of the spinal column to the skin in hopes of finding such a structure. As a result, many transducers of physical stimuli have been identified. Usually, these receptors are encapsulated structures that form the endings of the nerve. Besides the familiar receptors for sight, hearing, chemical concentrations, i.e., smell and taste, the following receptors have been identified in the skin. Collectively, they provide the information for what is called the sense of touch.

Meissner Corpuscles are the receptors that provide the *light touch*, such as the response of the skin to the soft stroke of a feather. They have a very low sensitivity threshold; they fire with the faintest touch. There appear to be different types of these receptors, classified by whether they respond to steady state or sinusoidal stimuli. *Pacinial Corpuscles* are pressure sensors that may provide the sense known as *deep touch*. They are sensitive to vibration also. These corpuscles consist of nerve endings surrounded by many layers of flattened cells about 0.5 μm across. Deformation of the corpuscles causes the nerve terminal to fire. *Merkel's Disks* are another type of tactile sensor. *Root Hair Plexuses* are windings

of the end of a nerve fiber around the root of a hair. They provide tactile reception, and detect changes in pressure and movement.

Ruffini Corpuscles are sometimes identified as the receptors that sense heat. They are generally bulb shaped, and consist of nerve endings surrounded by several layers of flattened satellite cells. *Krause Corpuscles*, also known as *Krause's end bulbs*, are thought to sense cold. Similar transducers have been found internally. *Golgi tendon organs*, found on muscle fibers, change muscle tension into an electrical signal.

The configuration and shape of the ends of most afferent (sensory) nerve fibers change with the function that the receptor performs. Some examples are simple unmyelinated extensions of the axon, branching or spiraling fibers, or flattened plates. The electrical output of a receptor is termed the generator potential. Its transfer characteristic also changes with the function of the receptor. Some distinguish between static and time-varying stimuli. Some respond primarily to the rate of change of stimuli. Some have precise thresholds. Others respond to stimulus changes in one direction only. The energy form to which the receptor is primarily responsive is called the *adequate stimulus*. A receptor cell may respond to other physical variations, but only at higher magnitudes of stimulation. The magnitude of generator potential is proportional to the log of the stimulus amplitude.

B. FREE NERVE ENDINGS

No receptor yet has been found for the transduction of the pain signal. The best theory at this time is that the nerves that are sensitive to pain have bare nerve endings (as opposed to neurons that end at receptors.) Along with the skin, free nerve endings innervate the connective tissues of the body. Bare nerve endings are

sensitive to certain chemicals, such as potassium, histimine, and prostaglandin, and to electrical stimulation. An injury to the body releases the hormone prostaglandin. The prostaglandins sensitize the bare nerve endings, thus decreasing the magnitude of the stimulus needed to cause the nerve to fire. Prostaglandin also causes the capillaries to swell, which increases the flow of blood to the affected area. The infusion of blood increases the pressure at the site, which aggravates the nerve endings and causes them to fire. Aspirin works by decreasing the release of prostaglandin. The decrease makes the nerve endings less sensitive, which raises the firing thresholds back towards normal levels. Also, the decreased level of prostaglandin slows the attraction of blood to the area of injury.

C. FIBER TYPES AND SIGNAL TRANSMISSION

Different types of afferent nerve fibers carry different sensory messages to the brain. Inputs from the sense of touch, position, and vibration are carried by *large* myelinated *Type A* fibers. Two different fiber types provide for the propagation of a *fast signal* and a *slow signal* from the free nerve endings in the skin to the brain. *Small* (~ 4.5 μm) myelinated *Type* A_δ fibers conduct fast (propagation velocity = 6 - 30 m/sec,) intermittent pain impulses. These signals are sensed in the brain as sharp and localized pain. The smallest (~ 1.8 μm) unmyelinated afferent nerve fibers are *Type C* fibers. Type C fibers conduct slow (propagation velocity = 0.5 - 2 m/sec,) continuous pain signals. These signals ultimately provide long-lasting, and not localized, pain sensation. Also, Type C fibers form a complex, overlapping group that may further delay the propagation of the pain signal.

The brain center for pain is unknown. However, propagation of pain signals has marked distinct areas in the *thalamus*, the upper end of the brain stem. The thalamus functions as switching network and chooses the correct destination for each signal in the *cerebral cortex*. Additionally, it has some circuits that process signals of pain directly. Although the specific neurons for pain have not been identified, most of the processing of pain signals occurs in the cerebral cortex. The cerebral cortex is a thin, convoluted layer of neurons forming the outermost part of the *cerebrum*; the highest, largest part of the brain.

The part of the brain stem just below the thalamus is called the *midbrain*. In the top of the midbrain is the periaqueductal gray matter (PAG). The PAG surrounds a channel (the Sylvian Aqueduct) that allows the flow of CSF through the midbrain. When a pain signal passes through the thalamus, the PAG produces *enkephalin*. The enkephalin descends into the *Raphe nuclei*, which are neurons that produce serotonin. When stimulated by enkephalin, the Raphe nuclei increase production of serotonin. The serotonin descends into the dorsal horn (side) of the spinal column, which is the side through which all sensory nerve tracts pass on the way to the brain. In the spinal cord, the neurotransmitter serotonin stimulates the release of enkephalin. The endorphin then interferes with receptor sites of postsynaptic neurons in the spinal column, reducing the upward transmission of further pain signals through the spinal column.

D. ENDORPHINS

Endorphins (***ENDO***geneous +mor***PHIN***e) are opiate-like substances that the body produces in response to pain. They work by blocking the chemical receptor sites on the postsynaptic membrane, thus preventing neurotransmitters from having an effect at those sites. Several dozen have been identified since the first

endorphin, Enkephalin, was identified in 1975. Different endorphins block different neurotransmitters. In particular, enkephalin blocks the effect of Substance P. Endorphins diffuse into the cerebrospinal fluid, which flows around the brain and spinal cord, and so block neurotransmitters at sites remote from the point of their release. The transfer of CSF from an anesthetized animal to a non-anesthetized animal results in anesthetization of the recipient. *Opiates* function in the same way as endorphins; blocking the function of neurotransmitter in the nerves of the spinal cord and brain. *Local anesthetics* affect neurotransmitters in the synapses of the nerve connections around the area of injury, thus preventing outbound pain signals from leaving the site of the injury.

E. REFERRED PAIN

Along with the periphery of the body, receptors and afferent neurons innervate the viscera. There are far fewer of these neurons, and they do not bring about sensation in the ordinary way. Instead, they convey information on the state of the viscera to the autonomic nervous system. Sometimes direct pain is perceived as a dull sensation due to impulses carried by visceral afferent neurons. Viscera is relatively insensitive to pain such as from a cut or burn on skin.

The visceral sensory neurons run up the spinal cord in tracts (Figure 3.6.a) that also contain neurons from receptors and free nerve endings in the skin. Sometimes, the transmissions from receptors on the viscera will trigger the afferent neurons from the free nerve endings in the skin to fire also. The response from these neurons then travels to the brain in parallel with the signals from the viscera, and registers as pain. Since this pain signal is from the sensory neurons that normally signal the stimulation of the free nerve endings on the skin, the brain perceives the pain as a sharp, stabbing pain on the corresponding area of the skin.

Sensation generated in this manner is *referred pain*. In addition to triggering sensory neurons from the skin, the nerves from the viscera might trigger the reflex arcs with motor neurons in the same manner, which would cause the muscles over the internal area to tense. This is the mechanism that causes pain and muscle contractions in the limbs, especially the left arm, when heart attacks are about to occur, i.e., when the heart is signaling the autonomic nervous system that it is in distress. Patches of skin at roughly the same height above the ground plane that are innervated by nerves that enter the dorsal root of the spinal column at the same point are called *dermatomes*.

A similar signal coupling effect could explain the phenomenon of pain in *phantom limbs*. Although the limbs are gone, the remainders of the afferent nerves that once innervated those limbs are still in place. Other nerves synapsing nearby might cause these nerves to trigger, sending the message to the brain that pain exists in the phantom limb.

VI. COMPLEMENTARY NEURAL THEORIES

A. LIMITATIONS OF CONVENTIONAL NEURAL THEORY

According to Robert Hecht-Nielsen, a leading authority on neural network theory,

> ...the brain is composed of networks of neurons. However, these neurons are much more complicated than are the processing elements used in neurocomputing, and their functions are not yet understood....A good way to think of the brain is as an exceedingly complex object built using an alien technology so advanced that we are only now, after more than a century of concentrated study, beginning to understand its simplest components [Ref. 9:p. 12].

Research in the area of neural communication and the electrical modeling of those methods has not yet suggested explanations for a large number of unexplained bioelectric phenomenon. Bioelectric fields, electric currents in the skin, regrowth and repair of damaged body parts, and accumulated anecdotal evidence of fringe sciences cannot be explained by conventional neural theory. Thus, either neurons communicate in some manner(s) not yet known, or other electric systems of unknown structure exist in the body.

Research into both trains of thought has persisted for decades. The reason for this research is summarized by Dr. Richard Borgens of Purdue University, a leading researcher of bioelectric fields and currents, in an attack on the opinion of another authority in the field of bioelectricity, Dr. Robert Becker. The two have quarreled in medical and scientific journals for decades, although both have made significant contributions to their field.

> Unfortunately, the notion of this group, that externally measured "bioelectric potentials" are produced by the nervous system, has tenaciously hung on in certain less critical circles -- partly because of its expansion into a more global approach to medicine, pathology, psychology, and even parapsychology and extrasensory perception ....Theories that have such all-encompassing scope seem to have appeal; however, in general (as in this particular case), they may have little scientific support. [Ref. 14:p. 32.]

Actually, no theories (based on specific cases) have been proven to explain the general causal mechanism of the body's electric fields and currents. *Credible* research into the causal mechanisms of these fields and currents has been ongoing since 1940, when medical doctors from Harvard University and mathematicians from the Massachusetts Institute of Technology began an effort to investigate the combined effects of digital and analog electrical communications in the body.

B. BIOFIELDS AND CURRENTS

The overall electric field of the human body is more positive at the head with respect to the periphery of the body. Also, the field around the head itself is more positive from front to back by about 2 VDC [Ref. 15:p. 116]. The strength of this field increases with physical exercise, decreases during sleep, and may decrease to zero or reverse polarity during the application of general anesthesia. Sleep, or unconsciousness, can be induced by the application of an external electric field of equal magnitude, but opposite polarity, to that of the head. The former Eastern-block countries have built and tested devices that induce electro-sleep and electro-narcosis for use on their military personnel. The usefulness of such a device would be to artificially ensure adequate rest for personnel in stressful situations (during service in a war zone, for example) without the use of drugs.

Some animals, such as the salamander, can regrow any of their limbs. At the site of amputation, the remaining uninjured cells dedifferentiate from their

specialized form, and coagulate into a *blastema*, an aggregate of unspecialized cells. The blastema then produces new specialized cells that grow to repair the injury. The mechanisms that instruct the blastema as to what kinds and quantities of cells to produce, and *how* to rebuild the injured part of the body are unknown. However, specific electric field and current patterns are detected around the blastema, and might provide the necessary instructions to the blastema.

C. OTHER NEURAL COMMUNICATION SCHEMES

1. Volume Conduction

The term *volume conduction* refers to a neural communication phenomenon that involves the tissue that surrounds the neurons in the communication process. However, the term is used by different researchers to refer to different realizations of this idea. Robert Plonsey, author of *Bioelectric Phenomena*, a classic text in the field of bioelectricity, proposes that although the current density is greatest at the dendrites and soma, much of the surrounding tissue is conductive, and that this volume of tissue supports the conduction of current to some degree. Some researchers in the field of electro-anesthesia have adopted the term to refer to the interaction of overlapping electromagnetic fields radiated from firing neurons. Other researchers have reported finding that neurotransmitter released at chemical synapses diffuses through extracellular space to trigger neurons that have no synapses with the triggering neuron. This idea can be extended to include the diffusion of the neurotransmitter into the cerebro-spinal fluid (CSF), to result in the firing of neurons at great distances from the triggering neuron.

2. Electrotonic Potential

The axon of some neurons, such as interneurons, is not readily distinguishable from the dendrites of that neuron, if indeed an axon exists all in these types on neurons. In these cases, no individual long fiber leads away from the soma. It is now believed that these types of neurons communicate with each other through the transference of the electrotonic potential, that is, the localized potential of the transmitting neuron at the site of communication. This type of communication is thought be utilized at gap junctions and at dendro-dendritic synapses. Since there is no chemical transfer involved, this type of communication is almost instantaneous. One possible implementation may be the synchronization of large numbers of neurons that must be signaled to fire at the same time, such as in the mechanism which generates of the heartbeat [Ref. 12:p.13]. However, due to the minute distances involved, this form of communication probably only functions within same *center* of the central nervous system.

The true difference between dendrites and the axon is not known. Usually, scientists restrict themselves to generalizations regarding the individual, longest, and myelinated fiber leading away from the soma when they discuss axons. When none of the fibers' from a neuron has a myelin coating, the axon for that neuron usually cannot be distinguished from the dendrites. However, the *characteristic*, or electrical, length of most dendrites is essentially *equal* to their physical length, while the characteristic length of most axons is much *shorter* than their physical length. This difference may be the fundamental difference between the two structures. The difference between electrical and physical lengths of axons may be the reason that pulsed, regenerative (at the Nodes of Ranvier)

propagation developed for axon conduction. As a consequence, there is no restrictive limit to the length of an axon.

D. PERINEURAL

Felix Mann, a medical doctor and past president of the Medical Acupuncture Society of Great Britain, points out that although the peripheral nervous system (PNS) has been mapped somewhat, it is still mainly an unknown system. He believes that portions of the PNS form a cutaneous nervous system unrelated to known sensory nerve pathways and sympathetic nervous system. This idea is reflected in the work of Russian researcher V. Ademko. He believes that the electrical properties of the skin form a combination low pass filter and rectifier that demodulates information from high frequency electromagnetic waves. He proposes that the skin detects (and transmits to the brain) *audio* information from radiation in the Ultra High Frequency (UHF) band, and *smell* information from radiation in the infrared frequency band.

Dr. Robert Becker, a leading (and controversial) authority on bioelectric phenomena, believes that the Schwann or Glial cells, which he terms *perineural* cells, provide an concentric, semiconducting coaxial cable around neurons, and form an electrical communication system for analog signals that complements the digital information transmission system of the known nervous system. He uses the perineural system to explain a number of uncertain, presumably electrical, phenomena, including the evolution of life on earth, and the conduction of the pain signal to the brain. While some medical and scientific professionals ridicule Becker and his work, many of his developments, such as electrode design and electrical stimulation of bone growth, are in common use today. Also, Becker was one of the first scientists to warn against possible adverse effects of

electromagnetic fields on the human body, which is now a commonly accepted viewpoint. In 1973, at the request of the Office of Naval Research (ONR), he served on the review committee for the U.S. Navy's proposed Project Sanguine ELF transmitter in northern Wisconsin. The committee's determination of probable electromagnetic radiation (EMR) hazards led to the cancellation of the project.

VII. OTHER ACUPUNCTURE MECHANISM THEORIES

A. HYPNOSIS

Many of those who do not believe in acupuncture as a physical process attribute its successful implementation to the power of suggestion of the practitioner, or the closely related *placebo effect*. Both of these explanations set forth that the effect is brought about as a function of the belief of the patient that the process will work. Experiments to prove this idea have relied on the insertion of needles at random locations, instead of precisely at the acupuncture points. These experiments have shown that acupuncture does work only when the acupuncture points are used. More evidence against the hypnosis hypothesis is the landmark treatment that brought acupuncture to the attention of the American people; the relief of the post-operative pain of James Reston in 1971. Acupuncture works in the same percentage of people who do not understand the language of its practitioner as in the percentage of people who do. Also, acupuncture works in children who are too young to speak, and has been used successfully to treat domesticated animals for thousands of years.

B. GATE THEORY

Large, myelinated Type A nerve fibers carry electrical signals from receptors to the spinal column. Pain signals from free nerve endings are carried by smaller myelinated type A_δ and small, unmyelinated Type C fibers. There is some evidence that the signals carried by large fibers get preferential treatment in synapses in the spinal column. Stimulation of acupuncture points triggers the receptors in the skin. The receptors transmit their electrical output on large Type

receptors in the skin. The receptors transmit their electrical output on large Type A fibers. As these fibers enter the spinal column in the dorsal root, the signals they carry block the signals carried by small fibers from free nerve endings at the site of the painful stimulus.

C. PERINEURAL

In 1961, the U.S. Army suggested to Dr. Becker that the explanation for acupuncture might be a manifestation of his broader theories on electrical fields and currents. After laboratory testing, he agreed, and proposed that the perineural cells form the anatomical structures that correspond to the traditional meridians of acupuncture. Additionally, he suggested that the perineural system is responsible for the conduction of the pain signal to the brain, and that the acupuncture points are the specific locations of specialized perineural cells which function as amplifiers to boost the pain signal. Inserting metal needles in the acupuncture points then shorts out those particular amplifiers, preventing the further transmission of the pain signal. His acupuncture mechanism theory does not account for the fact that the meridians used for treatment usually do not lie along the same path, or even the same part of the body, as the pain signal from the unwell body part. Also, such an explanation does not account for the successful use of other stimulation methods, such as pressure, or needles made of bone or stone. Similarly, Dr. Mann and V. Ademko, believe that unmapped portions of the peripheral nervous system form the conduction path of the traditional acupuncture meridians.

D. BRUCE POMERANZ

The gradual build-up of pain resistance during the administration of acupuncture could mean that acupuncture induces the brain and spinal cord to produce a substance that builds up in the body to raise the pain threshold. The majority of those Western scientists and doctors who believe that acupuncture works agree with this idea. In 1979, Bruce Pomeranz of the University of Toronto lowered the painkilling ability of acupuncture in laboratory animals by injecting *naloxone* into the CSF of those animals. Naloxone is a drug that blocks the receptor molecules for opiates and endorphins, especially enkephalin, at postsynaptic membrane sites. He also found that different rates of stimulation of the acupuncture points seemed to correlate to the production of endorphins in different parts of the CNS, i.e., different acupuncture stimulation frequencies block the pain signal at different places. His work is well-accepted as the best available explanation to date of the phenomenon of acupuncture.

VIII. CONCLUSION

On the basis of the reported research results, the electrical acupuncture mechanism proposed in the introduction appears unlikely. This occurred because the theory was based on an inadequate knowledge of the practice of acupuncture and too simplistic a model of nervous system conduction. It appears unlikely that acupuncture needles function as antennas, since stone, bone, and bamboo needles, as well as heat massage, and ultrasound, are equally effective stimulators of acupuncture points. Twenty to thirty minutes of stimulation of the acupuncture points are required to achieve a gradual build-up of pain resistance. If the mechanism of acupuncture was due to signal-to-noise ratio (SNR), the pain reduction effect should begin immediately when a needle is first inserted. Also, the manipulation of the needle is required to *start* the effect; it is not just used periodically to keep the electrical connection clean. Furthermore, the required manipulation of the needle implies that background electromagnetic radiation is not a sufficient stimulus to induce the needed level of trauma at acupuncture points. Acupuncture points usually are not located along the apparent route of the pain signal to the brain. Any obscuration of the pain signal by coupled electromagnetic noise would have to be a function of processing that occurs in the brain, not a function of interference with the pain signal as it is conducted through the periphery of the body.

The *telegraph line of electrical impulses* model of the nervous system originally was proposed by Helmholtz in 1868. The author assumed a similar neural communication scheme at the time his acupuncture mechanism theory was

presented. The actual method of communication between neurons is quite different. Although neural communication is still poorly understood, it is known to be a complicated phenomenon involving many biological and electrical processes.

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